



Original Article

External dose assessment for workers dismantling the bio-shield of a commercial power nuclear reactor: Case study of Kori-1, Korea

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ABSTRACT

The license for Kori-1, the first commercial reactor in Busan, Korea, was terminated in June 2017; therefore, preparations are being made for its decommissioning. Because the radioactivity of Bio-shield varies greatly throughout the structure, the doses received by the workers depend on the location, order, and duration of dismantling operations. Thus, a model for evaluating the worker external dose during the dismantling of the Kori-1 bio-shield was developed, and work scenarios for dose assessment were designed. The Dose evaluation code VISIPLAN was used for dose assessment. The dose rate around the bio-shield was evaluated and the level of exposure to the operator was evaluated according to the work scenario. The maximum annual external dose was calculated as 746.86 mSv for a diamond wire saw operator under dry cutting conditions, indicating that appropriate protective measures, such as changing dismantling sequence, remote monitoring, shield installation, and adjustment of work team are necessary for the safe dismantling of the bio-shield. Through these protective measures, it was found that the worker's dose could be below the dose limit.

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1. Introduction

When a nuclear power plant (NPP) reaches the end of its design life, its safety must be evaluated to determine whether it should undergo life extension or permanent shutdown. The NPP decommissioning industry is now more prevalent than ever in the nuclear power industry. To date, approximately 173 units are permanently shutdown and 115 unit are undergoing decommissioning around the world [1]. Although Korean research reactors, such as Korea Research Reactor-1&2 (KRR-1&2), have been decommissioned [2–4], Kori-1 is the first case of decommissioning a Korean commercial NPP. Kori-1 was commissioned in 1978 with an operating license that terminated in June 2017. Korea Hydro & Nuclear Power (KHNP)—the owner of Kori-1—decided to not apply for life extension of Kori-1, so they are preparing for its decommissioning. Fig. 1 shows the history of Kori Unit 1 and its upcoming schedule [5]. Unfortunately, the experience gained from decommissioning Korean research reactors is not directly applicable to Kori-1 because research and commercial reactors require different approaches for decommissioning owing to differences in reactor power, design,

and level of activation. Therefore, much preparation is necessary for the decommissioning of Kori-1.

The bio-shield is the wall that surrounds the reactor, shielding against external doses during reactor operation by absorbing neutrons emitted from the reactor. The bio-shield has a long lifespan, but its radioactivity varies greatly throughout the structure. Because the bio-shield is so large, it takes a long time to dismantle, which increases exposure to workers. Therefore, the dose that would be received by workers should be assessed before dismantling.

Both internal and external exposures are important in evaluating worker doses. External exposures are caused by gamma-emitting radionuclides (e.g., ^{60}Co , ^{152}Eu , and ^{154}Eu) in the radioactive concrete, and internal exposures are caused by beta-emitting radionuclides (e.g., ^3H , ^{14}C , and ^{55}Fe) contained in dust generated during dismantling. In this study, we focused on the external exposure to workers, performing dosimetry according to computer simulation. A model for evaluating the external dose to workers during dismantling of the Kori-1 bio-shield was constructed, and a scenario for dose assessment was designed. The three-dimensional (3D) ALARA evaluation code VISIPLAN (SCK•CEN; Mol, BEL) was used for dose assessment. The dose rate around the bio-shield was evaluated, and the exposure to a worker was evaluated according to the scenario.

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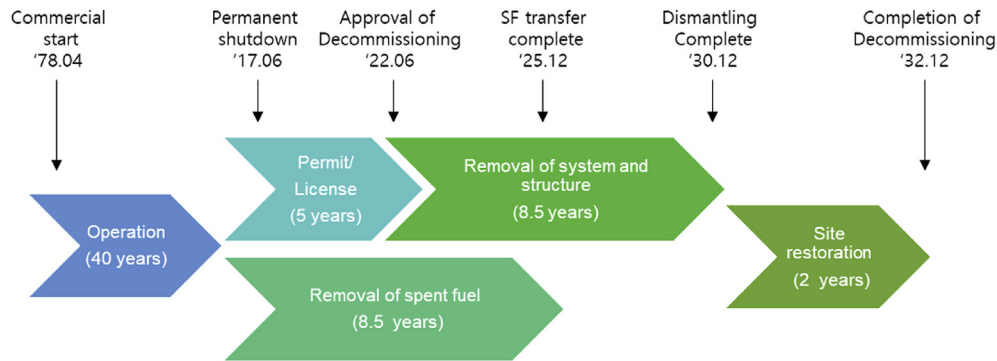


Fig. 1. Kori Unit 1 decommissioning and dismantling schedule.

2. Methods and materials

2.1. Simulation tools and methods

For the safety evaluation of workers dismantling the bio-shield, the study was performed using the neutron transport code MCNP and the dose evaluation code VISIPLAN as shown in Fig. 2. First, the structure of the target Kori-1 bio-shield was analyzed, and a worker scenario was designed. Based on this, the radioactive inventory was evaluated using MCNP6. Based on the geometric structure (Fig. 3), work scenario, and radionuclide data, the dose rate and external dose to the worker was derived using VISIPLAN.

2.2. Radioactive inventory calculations

The probabilistic code, MCNP, was used to evaluate the response of the neutron flux to each part of the simulated bio-shield geometry. Because there is no actual data for the activation of the Kori-1 bio-shield, the radioactivity must be evaluated through simulations based on the surrounding geometry, i.e., the reactor flux onto the bio-shield. MCNP6 is suitable for probabilistically evaluating the reactions between the bio-shield and neutrons generated by the reactor over a long period of time [6,7]. The concrete composition was prepared using the standard concrete nuclide composition ratio of ANSI/ANS 6.4, and the impurity was calculated using the CASMO-3 code [8]. In previous studies, three major long-lived nuclides (^{60}Co , ^{152}Eu , and ^{154}Eu) in the Kori-1 bio-

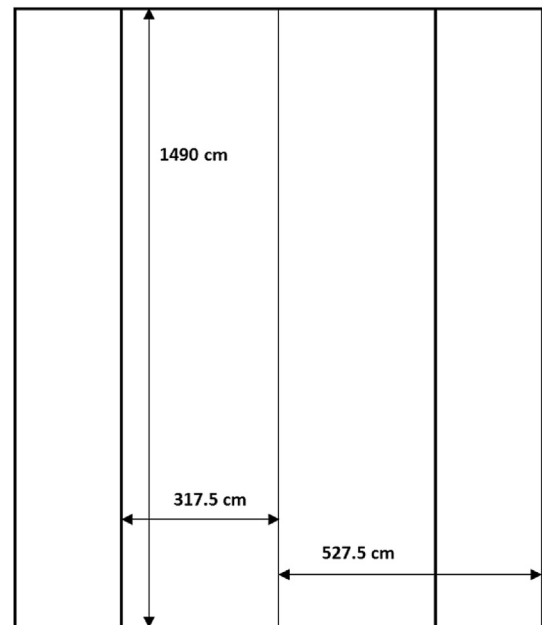


Fig. 3. Geometry of bio-shield.

shield were analyzed using MCNP6, and the resulting gamma radionuclide distribution is shown in Fig. 4 [9,10]. The three

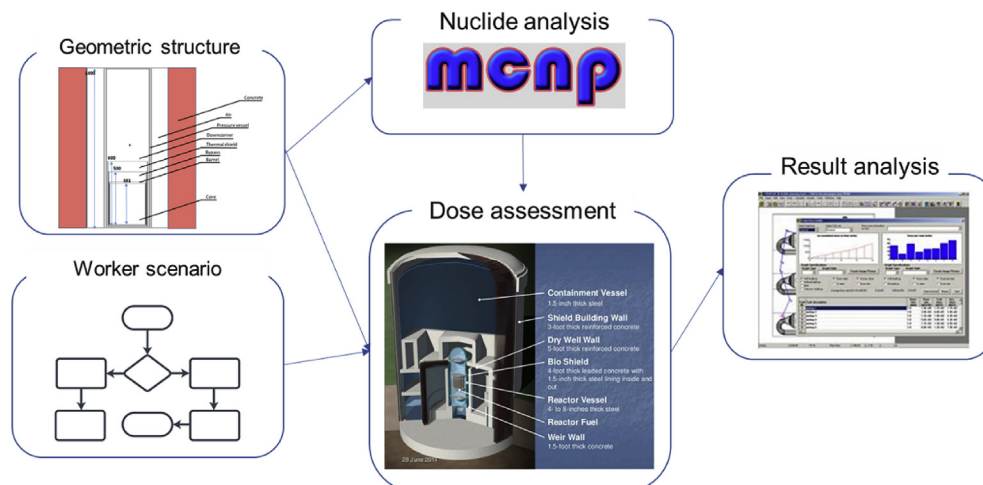


Fig. 2. Scheme of research process for worker dose assessment.

nuclides are those that are expected to be contaminated at high concentrations upon decommissioning, based on the analysis of other bio-shields. In addition, considering the external dose coefficient, the nuclide expected to lead to the highest exposure to the worker was considered. The total radioactivity was less than 0.1 Bq/g at the 397 cm region. The maximum radioactivity for ^{60}Co , ^{152}Eu , and ^{154}Eu were 4.53×10^3 Bq/g, 14.2 Bq/g, and 0.486 Bq/g, respectively.

Because the results of the previous study were obtained just after 40 years of operation, at the time of decommissioning, the radioactive isotopes decayed during the period from permanent shutdown to the actual decommissioning. In the decommissioning schedule of Kori Unit 1, the dismantling of the radioactive part begins after the spent fuel is taken out. Therefore, we considered two cooling periods, one of 8.5 years from the time of permanent shutdown and one of 13.5 years during which the dismantling is expected to be completed, as shown in Fig. 1. Based on the radioactivity obtained using MCNP6, the external exposure assessment for workers dismantling the bio-shield was performed.

2.3. Methodology of dose assessment

For the bio-shield worker dose assessment, the distribution of the dose was analyzed using the 3D ALARA evaluation tool, VISIPLAN. VISIPLAN uses an internet interface to remotely calculate doses and transmits the results of 3D data, allowing users to calculate doses in 3D scenarios. The methods used in the dose assessment take into consideration the position of the worker, the duration of the work, and the geometric and source distribution changes in the 3D computer simulation of the workplace, based on the point-kernel calculations [11,12]. The input parameters for analyzing the dose rate using VISIPLAN are shown in Table 1. The radioactivity input to VISIPLAN was obtained by dividing the bio-shield into 60 cells and averaging the radioactivity obtained from the MCNP simulation over each cell.

Based on the dose rate data obtained using VISIPLAN, the dose to a worker dismantling the bio-shield was evaluated as:

$$D_t = \sum_{x=1}^n D_x T_x \quad (1)$$

where D_t is the entire external dose to a worker dismantling the bio-shield (mSv), D_x is the external dose rate to a worker performing specific subtask x (mSv/h), and T_x is the time spent on subtask x (mSv). The dose received by the worker was determined from the dose rate and exposure time spent during each process of dismantling, for which the dose rate was determined according to the position of the worker doing that task.

Depending on the task definition, the external dose for workers will change considerably; therefore, the assumptions and decisions made in the evaluation are important. First, a decision on how to work is required. Among the several available methods for dismantling the Bio-shield, diamond wire saw (DWS) cutting, which is a suitable method for dismantling a large-scale structure, was considered. DWS cutting can be operated as a wet cutting method (using water for cooling and debris collection) or a dry cutting method (using only a dust-collecting device). By comparing the work times of the two methods, the difference in dose received by the operator can be obtained. The two cutting methods are compared in Table 2 [13,14].

As shown in Table 3, work scenarios for bio-shield dismantling can be constructed considered based on DWS cutting [15]. For bio-shield dismantling, two DWS operators and one assistant were considered to perform the task in the following scenario. All work was assumed to be performed continuously, i.e., preparatory work, drilling, and concrete lifting were performed simultaneously for different sections.

Table 1
Characteristics of Kori-1 bio-shield.

Structure	Annular Cylinder
Materials	Concrete
Height	1487.5 cm
Inner diameter	317.5 cm
Outer diameter	527.5 cm

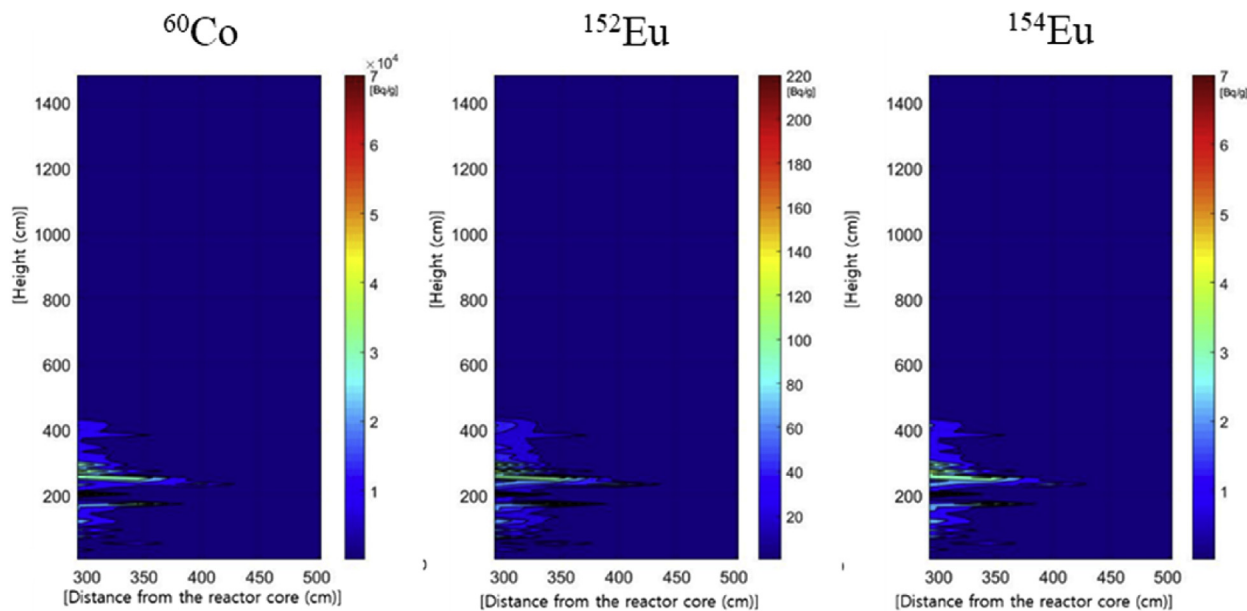


Fig. 4. Radioactivity distribution in bio-shield (Bq/g).

Table 2
Characteristics of wet and dry DWS cutting.

	Wet Cutting	Dry Cutting
Setup time	4 Manhour	
Cooling system	Water	Cold compressed air
Average Cutting rate(m ² /h)	1.11	0.78
Wire life time(m ² /m)	~1.5	~1
Secondary waste	Contaminated effluents Induced by sludge collection and treatment system (filtration, drying)	Induced by dust collection system (filters, confinement boxes)

Table 3
Scenario of dismantling bio-shield.

Type of works	Working hour (h)	Working distance from center (m)	Type of worker
Preparation	2	1.5	2 DWS operators
Drilling	1	2.5	1 assistant
Diamond wire saw Cutting	—	1.0	2 DWS operators
Block lifting	1	2.5	1 assistant

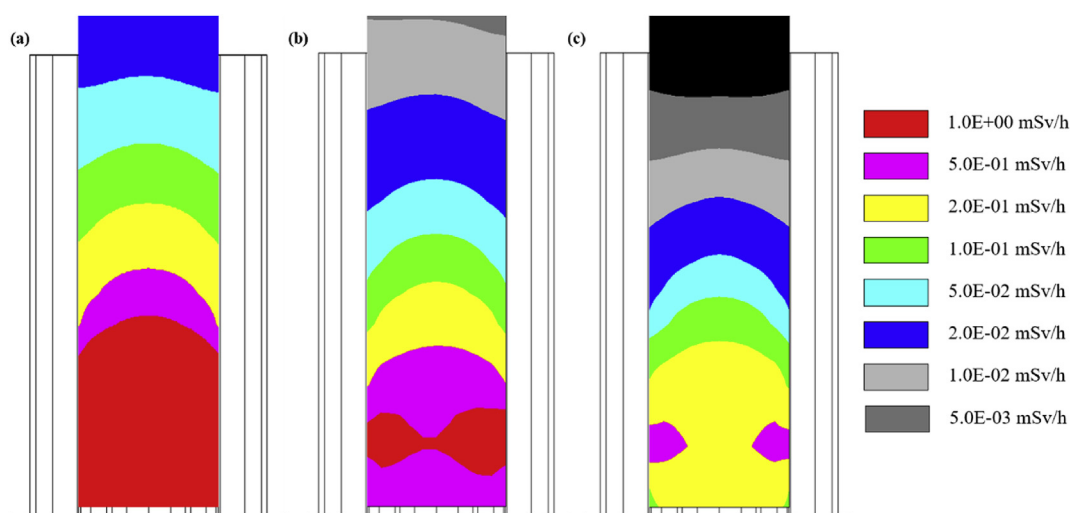


Fig. 5. Dose rate on bio-shield (a) after permanent shutdown, (b) after 8.5 years, (c) after 13.5 years.

Work time analysis also requires a definition of the order of task. To dismantle the concrete inside the bio-shield, it is assumed that the cutting is performed in the internal space inside the bio-shield, and from top to bottom. Each concrete section cut is assumed to be approximately 1 m³. In this work, the cutting plan is divided into inner and outer zones, and when the cutting is performed on a portion with high radioactivity, the inner zone is cut first. On average, three inner zone cuts and two outer zone cuts were performed per block.

In summary, 20 concrete blocks were created for the inner zone, and 27 concrete blocks for the outer zone at the same height. Considering the average number of cuts required per block, 60 cuts were performed in the inner zone and 54 in the outer zone. This is the number of operations required to perform a 1-m high cut; because the height of the bio-shield was approximately 15 m, 15 stacked concrete structures with height of 1 m were dismantled. Then, the doses at all heights were calculated, and the total time and exposure levels experienced by the worker during bio-shield cutting were calculated.

3. Results and discussions

The dose rate was assessed with VISIPLAN using the given geometry and the activation structure calculated by MCNP. Figs. 5 and

6 show the dose rates before and after removing the inner zones of the radioactive concrete during the dismantling process, and the maximum dose rates are listed in Table 4.

The dose rate in the work area appears to have decreased significantly after cooling compared with the rate before cooling. Prior to cooling, the maximum dose rate is up to 6 mSv/h at a height of 2.5 m, as in the MCNP simulation. In most areas, the dose rate is very high without protective measures and may exceed the worker's dose limit by ICRP [16–18]. After 8.5 years of cooling, the dose rate was reduced to 1.4 mSv/h, and after 13.5, to 0.82 mSv/h. However, even with lower doses after cooling, the dose rate may exceed the worker dose limit; therefore, detailed dose assessments are necessary for worker safety measures.

By comparing the dose rates before and after the cutting of the inner zones, it can be seen that the dose rate in Fig. 6 is significantly lower than that in Fig. 5, because most of the concrete radiation occurred within 1 m. By comparing the dose rate before and after cutting, it can be seen that the difference is more than 100 times. For the cooling time of 8.5 years, no other protective measures are required for the operator because the dose does not exceed 20 mSv, assuming an annual working time of 2,000 h when cutting the outside zone.

Fig. 7 shows the variation in dose with height and the distance from the wall. Moving toward the center, the dose from the hot spot at

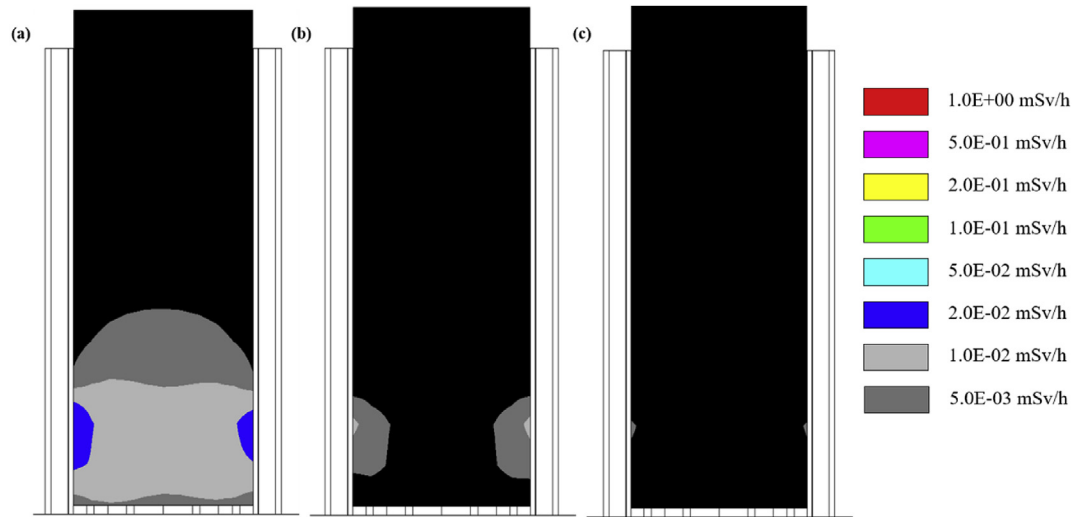


Fig. 6. Dose rate on bio-shield (a) after permanent shutdown, (b) after 8.5 years, (c) after 13.5 years (after removing the inner zones).

Table 4

Maximum dose rate comparison of evaluation results.

Cooldown	Dose rate interior on Bio-shield interior (mSv/h)	
	No cut considered	with inner zone cut
No cooldown	6.0	0.035
8.5 years cooldown	1.4	0.012
13.5 years cooldown	0.82	0.0056

2 m remains greater than that of the side wall, and the dose decreases exponentially with increasing height. At 3 m, the dose is the highest at the wall surface, but as the height increases, the dose farthest from the wall becomes the greatest. Fig. 8 shows the contributions of the three gamma-emitting nuclides to the dose rate at the height of 3 m. Of the three radionuclides evaluated, ^{60}Co had the highest effect, accounting for 99.7% of the dose rate; in contrast, ^{152}Eu and ^{154}Eu showed relatively low doses. This is similar to the ratio of activities provided by the MCNP radioactivity evaluation.

Table 5 shows the results of evaluating the worker's working time and dose based on the derived dose rate. The dismantling work time

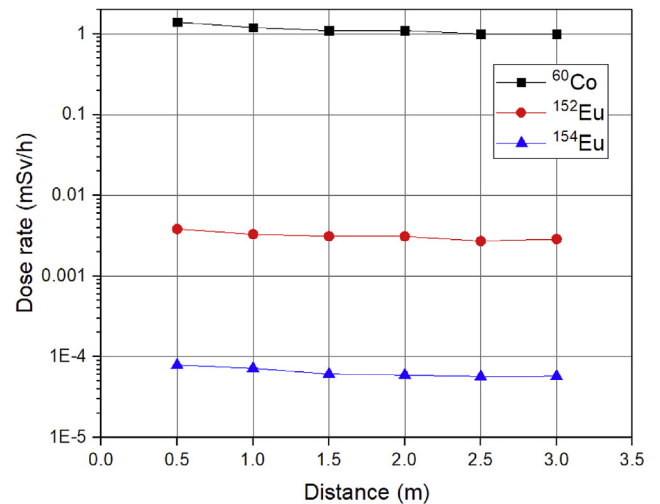


Fig. 8. Dose rate of inner space of Bio-shield with 2 m height.

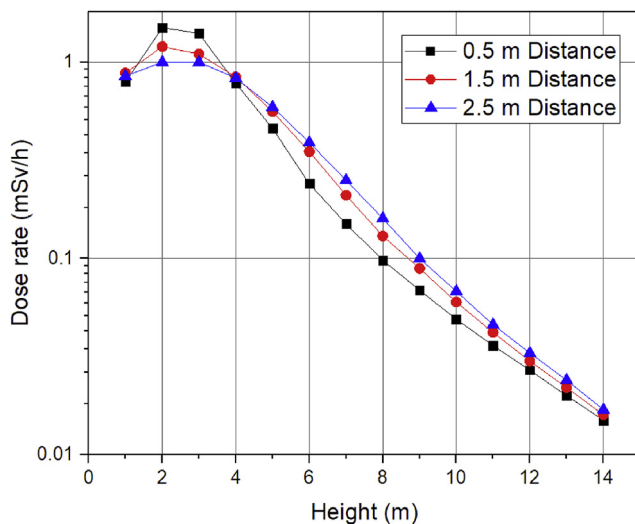


Fig. 7. Dose rate with height and distance from center.

was determined based on the number of blocks. The time required to cut one block was calculated as (preparation time + cutting time) \times number of cuts per block. The cutting time was calculated based on the cutting area (geometry segmentation) and cutting speed (Table 2). The working times were calculated as 5,159 h for wet cutting and 5,906 h for dry cutting. Therefore, the bio-shield dismantling process was estimated to take 2.57 years with wet cutting and 2.95 years with dry cutting, assuming annual work rates of 2000 h/years.

Because the work speed of wet cutting is faster, the high

Table 5

Working time and external dose during Bio-shield cutting.

	Wet cutting	Dry cutting
Working hour(hr)		
Preparation	3,420	3,420
Cutting	1,739	2,486
Total	5,159	5,906
External exposure(mSv)		
DWS operator	650.86	748.14
Assistant	649.54	746.86

Table 6
Dose reduction due to protective measures.

No protection measure	External exposure (mSv)	Dose reduction (mSv)	Reduction rate (%)
	746.86	0.00	0.0
(1) Change Dismantling sequence	484.85	−262.01	35.1
(2) Remote monitoring	426.73	−320.13	42.9
(3) Shield installation (lead 1.2 cm)	522.80	−224.06	50.0
(4) (1)+(2)	284.49	−462.37	61.9
(5) (1)+(2)+(3)	199.14	−547.72	81.0

activation parts are reached sooner compared with dry cutting, thereby increasing the dose rate; however, the work is completed ends sooner. Dry-cutting workers are estimated to receive 16% more dose than wet-cutting workers. The maximum annual dose for dry cutting worker, which occurs at the end of the project, was calculated as 748 mSv per person without any protective measure. The annual dose limit according to ICRP is 100 mSv for 5 years, or equivalently an annual average of 20 mSv. Because the calculation results exceed this average, there is a risk of exceeding the annual dose limit if the worker performs other tasks that expose them to a high dose. This indicates that adequate protection measures against radiation exposure are needed.

One way to reduce the work time is to change the dismantling sequence. In the previous scenario, the method of cutting the radioactive part and then the non-radioactive part was considered. Instead, a method that involves crushing the non-radioactive part first from the outside and then cutting the radioactive concrete can be used based on the radiological evaluation. In this case, because the time required for cutting the boundary between the radioactive concrete and the non-radioactive concrete can be eliminated, the working time can be shortened, and thus, a dose reduction can be expected.

Next, in the previous scenario, the cutting situation was analyzed next to the equipment; however, in the cutting process, the monitoring is performed by the operator without any additional work. Therefore, instead of being next to the equipment during this period, if the worker moves outside, where the dose rate is low and monitors the operation remotely, workers will not be exposed to the radiation during this time.

For the protection, for 0.5 mmPb, which is generally used, the protection is greater than 95% for low radioactivity; however, the main sources are 1.33 MeV and 1.17 MeV ^{60}Co in this case. For lead, the half-layer is very thick (1.2 cm) for ^{60}Co , and the efficiency of ^{60}Co protection in a 0.5-mmPb shield is approximately 3%, and 5 mm is 70% effective. Therefore, it would be better to consider installing shields rather than making protective clothing. If a 5-mm copper shield is installed, a 30% reduction is expected.

As a result of the evaluation of the considered protective measures, the dose reduction rates according to the protective measures can be compared, as listed in Table 6.

The baseline doses were based on the operator during the dry cutting, which had the highest dose when evaluating the exposure. The evaluation shows that the reduction rate according to the considered dose reduction method was approximately 35% for the change in the cutting sequence, 43% for the remote monitoring, and 70% for the shield installation. When all protection measures are considered, the dose was 1990 mSv, which was reduced by approximately 73.3%. However, in this case, the dose received by worker still exceeds the annual dose limit 50 mSv, but the present scenario is that three workers perform all the work. When multiple teams work alternately, individual worker doses can be lowered below the worker dose limit. To do this, it is possible to calculate the need for 4 teams and 12 workers, considering all the methods, and

by this measure, the worker's dose can be maintained below the annual dose limit.

4. Conclusions

In this study, the bio-shield dose rate was simulated using VISIPLAN to assess the worker dose for the safety evaluation of the Kori-1 bio-shield dismantling process. The maximum annual external dose was calculated as 746.86 mSv for a DWS operator performing dry cutting to dismantle the bio-shield. Therefore, appropriate protective measures, such as changing dismantling sequence, remote monitoring, shield installation, and adjustment of work team are necessary for bio-shield dismantling with dry cutting. Through these protective measures, it was found that the worker's dose could be below the dose limit. For the entire external dose received by a worker during bio-shield dismantling, the wet cutting method results in less dose, but secondary waste generation (126.7 L/m^2) must be considered [14].

By using the developed dose evaluation system, it was possible to secure the safety of the worker by confirming the dose to the worker before dismantling. It was also possible to perform radiological comparisons by deriving the doses for different equipment that can be considered in dismantling situations. These comparisons can be used to optimize the dismantling equipment and calculate the radiological costs accordingly. Because the simulated situation differs from actual plant operation, the evaluated dose and the actual dose may differ. Measured dose rates, which can be incorporated into VISIPLAN, can be used to obtain the actual dose distribution by correcting the external dose to match the actual measured value at a certain position. Depending on the used dose evaluation system, it is possible to use different inputs from other power plants as well as other targets for preliminary dose assessment.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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